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# TECHNICAL NOTE

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HEAT TRANSFER TO CYLINDERS IN CROSSFLOW  
IN HYPERSONIC RAREFIED GAS STREAMS

By Ruth N. Weltmann and Perry W. Kuhns

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HEAT TRANSFER TO CYLINDERS IN CROSSFLOW  
IN HYPERSONIC RAREFIED GAS STREAMS

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SUMMARY

A study was made of the heat transfer to cylinders in crossflow in a low-density wind tunnel for three gases of different molecular weight and accommodation coefficient at Mach numbers of about 5 with nitrogen, about 4 and 7 with helium, and about 6 with argon. These data cover the range of Knudsen numbers from free-molecule flow to almost continuum flow. Nusselt, Reynolds, and Knudsen numbers covered are  $0.01 \leq Nu \leq 10$ ,  $0.1 \leq Re \leq 1000$ , and  $0.001 \leq Kn \leq 15$ . The free-molecule flow data indicate an accommodation coefficient of about 0.9 for nitrogen, about 1.0 for argon, and about 0.4 for helium on a Chromel-Alumel thermocouple wire.

Temperature-recovery ratios were also measured over a range of Knudsen numbers from free-molecule flow to almost continuum flow. For free-molecule flow the ratio approaches a value that is close to that predicted by theory.

INTRODUCTION

Heat transfer in high-speed, rarefied gases is of interest for studies of material behavior, instrumentation, and flight performance at high altitudes. In problems of hypersonic flight, heat-transfer data for monatomic and for diatomic gases of different molecular weight and under conditions of different accommodation coefficient are of special importance. Since the accommodation coefficient depends on the surface condition of the body as much as on the gas properties, it is quite possible that the accommodation coefficients encountered in space flight will vary. For this reason heat-transfer studies were undertaken on three rarefied gases of different molecular weight and accommodation coefficient.

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In the transition- and slip-flow regions as well as in the continuum-flow region, heat-transfer data have to be obtained experimentally, since no theoretical solution exists in these flow regions for the determination of heat transfer to a cylinder in a viscous compressible fluid. Several papers on experimental work on the heat transfer to cylinders in crossflow at supersonic and hypersonic Mach numbers in these flow regions have been published for air (refs. 1 to 7) and for nitrogen (refs. 1 and 8).

In the free-molecule-flow region theoretical calculations have been made for heat transfer to cylinders in crossflow (ref. 9). These calculations show that in free-molecule flow the heat-transfer rate or the Nusselt number is a linear function of the Reynolds number and depends also on the accommodation coefficient. Although accommodation coefficients are reported in the literature (refs. 10 to 12), these reported values vary too much, probably because of insufficient control of the experimental conditions, to be used for heat-transfer calculations. Therefore in free-molecule flow heat-transfer data are usually also obtained experimentally and used to determine the accommodation coefficient for the prevailing experimental conditions. The extent of the free-molecule-flow region also is determined by heat-transfer measurements. The free-molecule heat-transfer and temperature-recovery data which were measured on cylinders in crossflow in rarefied gas streams at supersonic speeds (refs. 8, 9, and 13) agree well with the free-molecule-flow theory. The experimental heat-transfer data were obtained for nitrogen gas (refs. 8 and 13), and the temperature-recovery ratios were determined for nitrogen and helium gas (refs. 8, 9, and 13).

The object of this report is to compare heat-transfer data for cylinders in crossflow at hypersonic Mach numbers for gases of different specific-heat ratio, molecular weight, and accommodation coefficient. The experimental data extend into all flow regimes from free-molecule to almost continuum flow. This made it possible to determine approximate transition points from one flow region into another and also to obtain accommodation coefficients for the prevailing experimental conditions.

Since heat-transfer data were available for nitrogen (refs. 1, 8, 9, and 13), it was chosen as one of the three gases. This provided a check of the literature data and of the experimental technique used in this report, and also some additional heat-transfer data for nitrogen. Helium was chosen because of its low molecular weight and low accommodation coefficient. Argon was selected as the third gas, because it is monatomic like helium but has a high accommodation coefficient like nitrogen and a higher molecular weight than nitrogen. The heat-transfer and temperature-recovery data were determined at the following Mach numbers:  $M \approx 5$  for nitrogen,  $M \approx 4$  and  $7$  for helium, and  $M \approx 6$  for argon.

Static pressures in the gas stream ranged from 20 to 220 microns of mercury. Experimental determinations of time constants were made on bare-wire thermocouples in crossflow to determine the relations between Nusselt and Reynolds numbers for  $0.01 \leq Nu \leq 10$  and  $0.1 \leq Re \leq 1000$ . Temperatures were measured together with the time constants to obtain the temperature-recovery ratio (ratio of measured wire temperature to total gas temperature) as a function of Knudsen number for  $0.01 \leq Kn \leq 15$ . (Symbols are defined in the appendix.)

### TEST FACILITY

The test facility is a continuously operating low-density tunnel with available pressures of 0.02 micron of mercury at the no-flow condition ("ultimate vacuum") to a maximum of about 300 microns of mercury. The tunnel and pumping system are shown in figure 1. The test chamber is about 4 feet in diameter and 5 feet long and is provided with 20-inch-diameter access plates on each side for windows and instrument connections. The nozzle is attached to the front plate of the test chamber, so that the high-velocity jet discharges into the test chamber (fig. 1). Five oil-diffusion booster pumps are used to obtain the low pressure in the test chamber. The required forepressure and throughput are obtained by the use of mechanical pumps in combination with a two-impeller rotary blower. Poppet valves are installed between the test chamber and each booster pump to permit the use of one to five pumps. The volume flow rate of the group of five booster pumps as a function of pressure is shown in figure 2 for nitrogen, argon, and helium.

Two supersonic nozzles were employed. Nozzle 1, which was used for most measurements, produced a jet stream at a Mach number of about 5 for air or nitrogen. The design of this nozzle was similar to one described in the literature (ref. 14) for somewhat similar studies on nitrogen. Since the boundary-layer thickness increases with decreasing density, allowance was made in the design for the boundary-layer thickness encountered at these low densities. The nozzle throat diameter is about 0.2 inch and the exit diameter is about 1.6 inches. All reported measurements were made at a stream static pressure of more than 20 microns of mercury, since below this pressure the boundary layer became so great that it almost filled the cross section.

Nozzle 2 was a conical one and was used to check some of the helium data. The throat diameter is about 0.5 inch and the exit diameter is about 2.7 inches.

## MEASUREMENTS

The nozzle was calibrated by determining Mach number profiles transverse to the jet axis at different distances from the plane of the nozzle exit. The impact probe that was used to measure the profiles had a diameter of 0.1 inch. Thus the flow measured by this probe always remained in the continuum-flow region down to the lowest employed static pressures of about 20 microns of mercury in the jet stream. Thus, no free-molecule-flow or slip-flow corrections had to be applied to the impact-pressure measurements. However, the static-pressure measurements required corrections which were found by the following procedure. Assuming isentropic flow at least in the centerline of the jet, the Mach number can be obtained from the ratio of the total pressure upstream to the impact pressure downstream of the nozzle and also from the ratio of impact to static pressure downstream of the nozzle. The centerline Mach number was determined from the ratio of upstream total to downstream impact pressure. This Mach number together with the downstream impact pressure was then used to find the corrected centerline static pressure. This procedure was repeated to obtain a correction curve for the complete range of measured static pressures. The locally measured and corrected static pressure together with the locally measured impact pressure was used to obtain the local Mach number at all positions other than along the centerline of the jet.

Mach number profiles at about 1.2 inches downstream from the exit plane of the nozzle are shown in figure 3 for nitrogen, argon, and helium. Two profiles of nozzle 1 are shown for each gas at two jet centerline static pressures to show the effect of increasing boundary layer on the shape of the profiles and on the centerline Mach number. Nozzle 1 was designed for air or nitrogen to give a jet stream at  $M \approx 5$ . The profiles for nitrogen are flat over about 0.5 inch, and the centerline Mach number varied between  $5.0 \leq M \leq 5.3$  for  $20 \leq p_s \leq 150$  microns of mercury. Argon has a different specific-heat ratio from nitrogen. Therefore, with this same nozzle the Mach number profiles are not quite as flat as those for nitrogen. The centerline Mach number varied between  $6.0 \leq M \leq 6.4$  for  $20 \leq p_s \leq 100$  microns of mercury. Helium has the same specific-heat ratio as argon, but its molecular weight is very different from that of nitrogen or argon. Therefore, with this same nozzle, very poor Mach number profiles were obtained. The centerline Mach number varied between  $6.6 \leq M \leq 7.0$  for  $20 \leq p_s \leq 100$  microns of mercury. With the conical nozzle 2, the Mach number profiles for helium are flat over about 0.4 inch. Because of this nozzle's conical shape, the boundary layer almost filled the cross section at stream static pressures below 150 microns of mercury. Thus nozzle 2 could be used only over a very limited range of stream static pressures. The centerline Mach number varied between  $3.5 \leq M \leq 3.9$  for  $180 \leq p_s \leq 220$  microns of mercury. Since the Mach number profiles for helium in nozzle 1 are not flat, the validity of the heat-transfer data measured with this nozzle in helium might be questioned. However, the heat-transfer data for helium obtained with nozzle 2 check those that were measured using nozzle 1; therefore, it is felt that the helium heat-transfer data are valid.

The upstream pressures were measured with an oil manometer, while the downstream pressures were measured with a thermal-conductivity-type (Autovac) gage, which was calibrated for each gas against a McLeod gage at pressures less than 500 microns of mercury and against an oil manometer at pressures greater than 500 microns of mercury.

Seven thermocouple probes placed about 1.2 inches downstream from the nozzle exit were tested. Their diameters and materials are given in table I. No special treatment was applied to the bare-wire thermocouples. The junctions of the wires were butt-welded. The two smallest wire diameters were measured with a microscope and the others with a micrometer. All measurements were rounded off to the last place given in the table. The thermocouples constituted one side of a triangle which they formed with the two support wires. The thermocouple and the two supports were each about 1.0 inch long. The thermocouples were mounted normal to the stream of the jet, while the support wires were yawed at an angle of about  $45^\circ$ . To obtain a high Reynolds number and a relatively short time constant two of the specimens consisted of a large-diameter hollow copper cylinder with a 0.005-inch wall thickness and having a 0.0031-inch-diameter constantan thermocouple wire attached to it at mid-length.

Time constants were measured by inducing a step change in the wire temperature. The thermocouple wire was first shielded from the jet stream, so that it was at test chamber temperature. A sudden removal of the shield increased or decreased the temperature of the wire, depending upon the recovery temperature. The time constant of the step change was measured from the recorded response and interpreted as described in reference 15.

### CALCULATIONS

Reynolds numbers  $Re_{10}$  were calculated by using the viscosity at the total-temperature and the density at static-temperature conditions. Nusselt numbers  $Nu_{10}$  were calculated from the time constant by using the gas conductivity  $k$  at the total temperature. The values for gas viscosity, thermal conductivity, and other properties were obtained from references 10 and 16. The wire constants, such as specific heat, density, and thermal conductivity, were taken from reference 15. The static pressure corresponding to the respective centerline Mach number was used. Nusselt numbers and wire temperatures were corrected whenever necessary in the manner of reference 15 for end conduction losses and for the change in Mach number and static pressure along the transverse profile of the jet. These corrections resulted in a decrease in the measured Nusselt number. The maximum corrections that were applied to the measured values of the Nusselt number are given in table I for each thermocouple and gas. The wire temperature corrections were always positive and less than 1 percent for nitrogen and argon and less than 2 percent for helium.

The Knudsen number varies less with Mach number when expressed as a function of  $Re_{10}$  than as a function of  $Re_s$ . For  $2 \leq M \leq 8$  at

$$T_0 = 540^\circ \text{ R, the range of Kn for air and nitrogen is } \frac{1.90}{Re_{10}} \leq Kn \leq \frac{0.65}{Re_{10}},$$

$$\text{for argon it is } \frac{1.50}{Re_{10}} \leq Kn \leq \frac{0.70}{Re_{10}}; \text{ and for helium it is } \frac{1.95}{Re_{10}} \leq Kn \leq \frac{1.55}{Re_{10}}.$$

## RESULTS AND DISCUSSION

### Nusselt Number - Reynolds Number Relations

In subsonic continuum flow the empirical equation for heat transfer from gases to cylinders in crossflow is well established (refs. 1 and 15). The authors of reference 15 found experimentally that for Reynolds numbers between 250 and 30,000 in subsonic continuous flow

$$Nu_{10} = 0.48 Pr^{0.3} \sqrt{Re_0}$$

where  $Re_0$  is based on an evaluation of the gas density and viscosity at total temperature. In hypersonic flow, if  $Re_0$  is evaluated at conditions behind the normal shock,  $Re_0$  is almost equal to  $Re_2$ , since  $T_0 \approx T_2$ . Because  $Re_2$  is equal to  $Re_{10}$  ( $\rho_1 v_1 = \rho_2 v_2$ ), the relation between Nusselt and Reynolds numbers for supersonic flow in nitrogen, argon, and helium where  $Pr^{0.3} \approx 0.9$  can be approximated by the equation

$$Nu_{10} = 0.43 \sqrt{Re_{10}}$$

In free-molecule flow (refs. 8 and 9)

$$Nu_{10} = C Re_{10}$$

where  $C$  is independent of  $M$  at Mach numbers above 2 but is a function of the gas transport properties and thus varies for different gases.

The heat-transfer curve for nitrogen (fig. 4(a)) checks and augments the data that had been obtained for heat transfer to cylinders in crossflow at  $1.9 \leq M \leq 6.1$  in rarefied nitrogen (refs. 8 and 13) and at  $1.9 \leq M \leq 5.7$  in air (refs. 3 and 7). The data obtained in air at  $M < 2$  (refs. 1, 2, 4, 5, and 6) check fairly well also, but are not shown in figure 4(a). In free-molecule flow, the experimental data check the theoretically derived equation for heat transfer from circular cylinders oriented transversely to the stream for an accommodation coefficient of  $\alpha = 0.9$ . This agrees with some values given in the literature (refs. 10 to 12). Reference 8 also obtained the best fit between the experimental data and the theoretical curve when using  $\alpha = 0.9$ . All these data were obtained at  $M \geq 1.9$ , where the heat transfer in free-molecule flow is almost independent of  $M$ . The data for nitrogen (fig. 4(a)) indicate that the free-molecule-flow equation is applicable to a Knudsen number

of the order of 2 or above. At  $Kn < 2$  transition and slip flow set in, and the heat transfer is less than it would be in free-molecule or continuum flow. The slip-flow data obtained at  $M \approx 5$  agree fairly well with those of references 3, 7, and 8, which were determined at  $1.9 \leq M \leq 5.7$ . The experimental data for nitrogen indicate that complete continuum flow, so far as heat transfer is concerned, seems to occur only at Knudsen numbers of  $Kn \leq 10^{-3}$ . In most texts continuum flow is supposed to set in at  $Kn \leq 10^{-2}$ . This value is probably correct enough for most aerodynamic considerations, such as shock and boundary-layer formation, since the deviation in heat transfer from the continuum-flow curve is very small at  $10^{-3} \leq Kn \leq 10^{-2}$ .

The heat-transfer curve for argon (fig. 4(b)) is similar to that for nitrogen; the best fit in free-molecule flow is obtained with  $\alpha = 1.0$ . This value again agrees well with some values given in the literature (refs. 10 to 12). The heat-transfer data show that the free-molecule-flow equation is applicable at a Knudsen number of the order of 2 or above. In this case the slip-flow data do not extend into continuum flow, but the trend indicates that the continuum-flow region starts, as far as heat transfer is concerned, at  $Kn \approx 10^{-3}$ , since the transition- and slip-flow data have about the same slope and trend as those for nitrogen.

The helium heat-transfer curve (fig. 4(c)) looks somewhat different. In free-molecule flow  $\alpha = 0.4$  gives the best fit with the theoretical curve. This value appears reasonable, since the literature (refs. 10 to 12) reports values between 0.3 and 0.5 for experiments made without special surface treatment of the wires. It appears that a Knudsen number of the order of 10 or above is required for free-molecule flow in the helium gas; this limit is higher than the limits for argon and nitrogen. In transition and slip flow the Nusselt number is much lower than it is for nitrogen and argon, and the trend indicates that the curve will meet the continuum-flow curve at a Knudsen number of about  $5 \times 10^{-4}$ . Thus the regime of transition and slip flow for helium extends farther than those for nitrogen and argon. The data obtained with nozzle 2 check well those measured with nozzle 1.

The average deviation of a single observation is less than 10 percent for all three gases. The uncertainty in Nusselt number corrections for end conduction losses and Mach number profiles, and additional errors caused by inaccuracies in the determination of the jet velocity and static pressure might add an additional systematic error, which would be greatest for the helium data because of the steep Mach number profiles for helium in nozzle 1. Some other sources of error are failure to place the thermocouple in the center of the jet, inaccuracy in measuring the time constant, and errors in effective wire-diameter measurement due to lack of roundness and uniformity of wire and junction.



### Temperature-Recovery Ratios

The temperature-recovery ratio  $T_w/T_o$  is a function of the recovery factor  $r$ :

$$\frac{T_w}{T_o} = \frac{1 + \left(\frac{\gamma - 1}{2}\right)rM^2}{1 + \left(\frac{\gamma - 1}{2}\right)M^2}$$

For free-molecule flow a theoretical equation derived for the temperature-recovery ratio (ref. 9) shows it to be different for diatomic and monatomic gases, but independent of  $M$  at hypersonic Mach numbers. For  $M \geq 4.0$  for nitrogen (diatomic)

$$T_w/T_o = 1.165$$

For  $M \geq 5.0$  for argon and helium (monatomic)

$$T_w/T_o = 1.265$$

The temperature-recovery ratio for nitrogen is shown in figure 5(a) as a function of Knudsen number. The average deviation in  $T_w/T_o$  is less than 2 percent. The data obtained at  $M \approx 5$  check those from references 8 and 13. In continuum flow at  $Kn \leq 0.05$ , the temperature-recovery ratio approaches a value of about 0.965, which is in accordance with the temperature-recovery ratios obtained in supersonic airflow (refs. 5 and 6). In free-molecule flow the temperature-recovery ratio should theoretically approach a value of 1.165 for nitrogen (ref. 9). From figure 5(a),  $T_w/T_o$  appears to be 1.165 at  $Kn \approx 5$ , but seems to increase further with  $Kn > 5$ .

The data for the temperature-recovery ratios for argon and helium shown in figures 5(b) and (c) are less accurate and show a greater experimental spread than those for nitrogen in figure 5(a). The average deviation in  $T_w/T_o$  is about 3 percent. This is not surprising, since the jet Mach number profiles (fig. 3) are less flat for argon than for nitrogen and are not flat at all for helium, so that a small decentering of the thermocouple junction could have caused an error in the wire-temperature measurement. Figure 5 indicates that in the transition and slip-flow region the temperature-recovery ratios for helium are substantially higher (and displaced by a constant amount) than those for nitrogen and argon at any given Knudsen number. The free-molecule flow data of helium (ref. 9) were not used for comparison, since they were obtained at relatively low Mach numbers for which the temperature-recovery ratio  $T_w/T_o$  in free-molecule flow is less than 1.265.

## CONCLUDING REMARKS

The heat-transfer data obtained in nitrogen for cylinders in cross-flow at hypersonic Mach numbers check well the available data obtained in nitrogen and air. Thus heat transfer in nitrogen and air at temperatures below dissociation is the same for all practical purposes in all flow regimes.

The heat-transfer data obtained in argon follow closely those of nitrogen. The two gases have almost the same accommodation coefficients, namely 0.9 for nitrogen and 1.0 for argon, while they have different specific-heat ratios and different molecular weights.

Helium, with a low molecular weight compared with nitrogen and argon, was found to have a low accommodation coefficient of only 0.4. Thus the helium heat-transfer data in free-molecule flow differ by a factor of 2.5 from those of nitrogen and argon. This difference prevails throughout the transition- and slip-flow regions and only disappears at Knudsen numbers close to continuum flow. This suggests that the accommodation coefficient is principally responsible for the difference in heat transfer that was found between nitrogen and helium. In continuum flow the relation between the Nusselt and Reynolds numbers is expected to be the same for nitrogen, argon, and helium, since in continuum flow the accommodation coefficient is 1 for all gases. Thus, the heat-transfer data reported for helium seem to be representative for any gas and cylinder combination with a similar low accommodation coefficient.

Lewis Research Center

National Aeronautics and Space Administration  
Cleveland, Ohio, December 7, 1959

## APPENDIX - SYMBOLS

a	sound velocity, $\sqrt{\gamma RT}$
C	constant for hypersonic free-molecule-flow heat transfer (at about $M \geq 2$ ), $\frac{3gRPr}{\pi c_p}$ for diatomic gases and $\frac{2gRPr}{\pi c_p}$ for monatomic gases
$c_p$	specific heat at constant pressure
d	thermocouple wire or cylinder diameter
g	gravitational constant
h	heat-transfer coefficient
Kn	Knudsen number, $\sqrt{\pi\gamma/2} M/Re_s = \sqrt{\pi\gamma/2} \frac{M}{Re_{10}} \frac{\mu_s}{\mu_o}$
k	gas conductivity
M	Mach number, $v/a$
Nu	Nusselt number, $hd/k$
Pr	Prandtl number
p	pressure
R	gas constant
Re	Reynolds number, $dvp/\mu$
r	temperature-recovery factor
T	absolute temperature
v	velocity
$\alpha$	accommodation coefficient
$\gamma$	specific-heat ratio
$\mu$	viscosity
$\rho$	density

## Subscripts:

- o total conditions
- s static conditions
- w wire
- l free-stream conditions
- 2 conditions behind a normal shock
- 10 refers to fact that density is evaluated at free-stream conditions and that  $\mu$  and  $k$  are evaluated at total temperature

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TABLE I. - THERMOCOUPLE DIAMETERS AND  
MAXIMUM NUSSELT NUMBER CORRECTIONS

Gas	Material (a)	Diameter of cylinder, in.	Maximum corrections applied to Nu, percent
N <sub>2</sub> A He	CA	0.0011	4.0 4.0 2.0
N <sub>2</sub>	CA	0.0031	5.0
N <sub>2</sub> A He	IC	0.0050	15 16 15
N <sub>2</sub> A He	IC	0.0156	30 30 20
N <sub>2</sub> A He	IC	0.0620	40 35 40
N <sub>2</sub> He	CuC	0.148	1.0 1.0
N <sub>2</sub> He	CuC	0.492	1.0 1.0

<sup>a</sup>CA, Chromel-Alumel; IC, Iron-Constantan; CuC, Copper-Constantan.

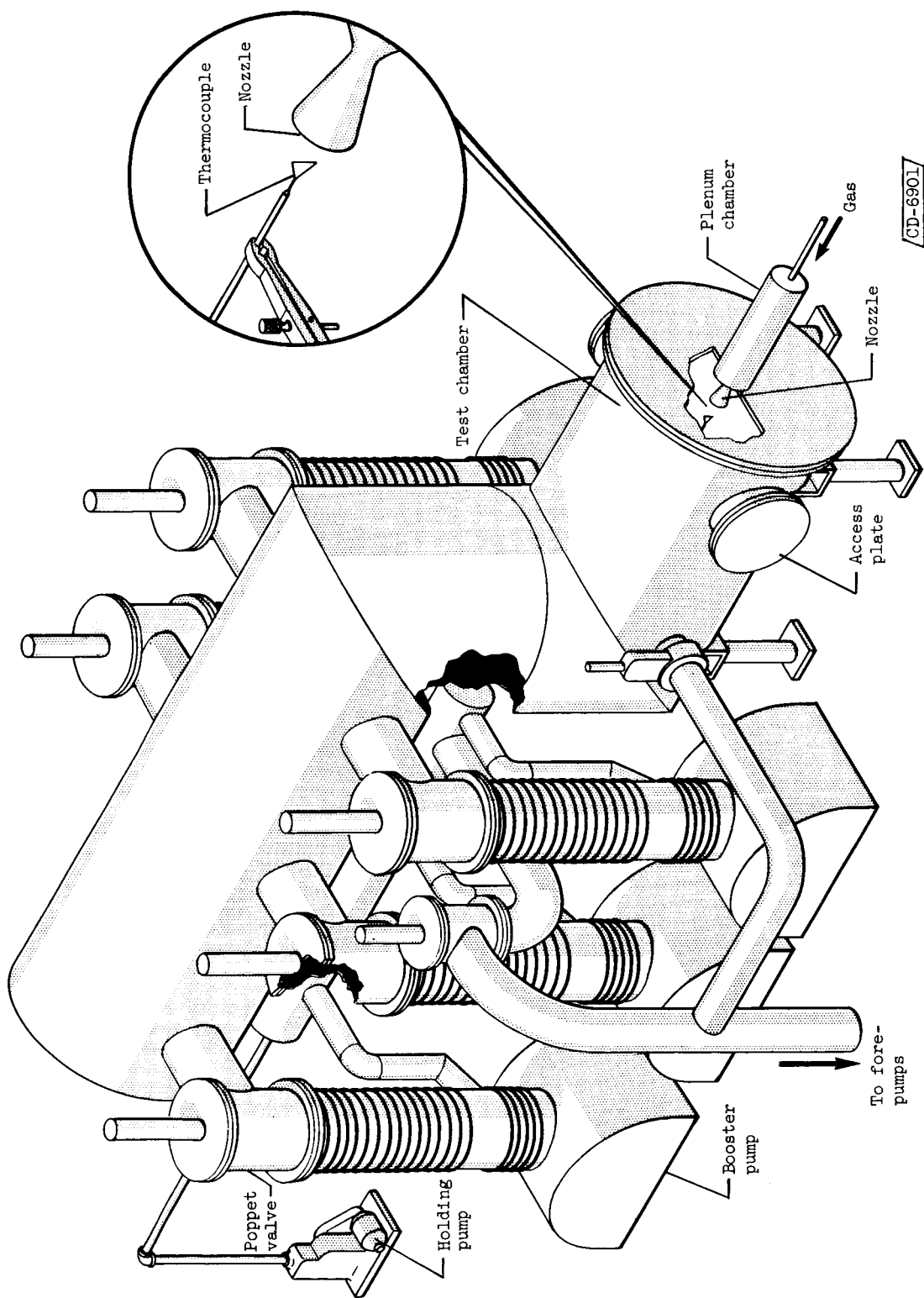


Figure 1. - Test facility, continuously operating low-density tunnel.

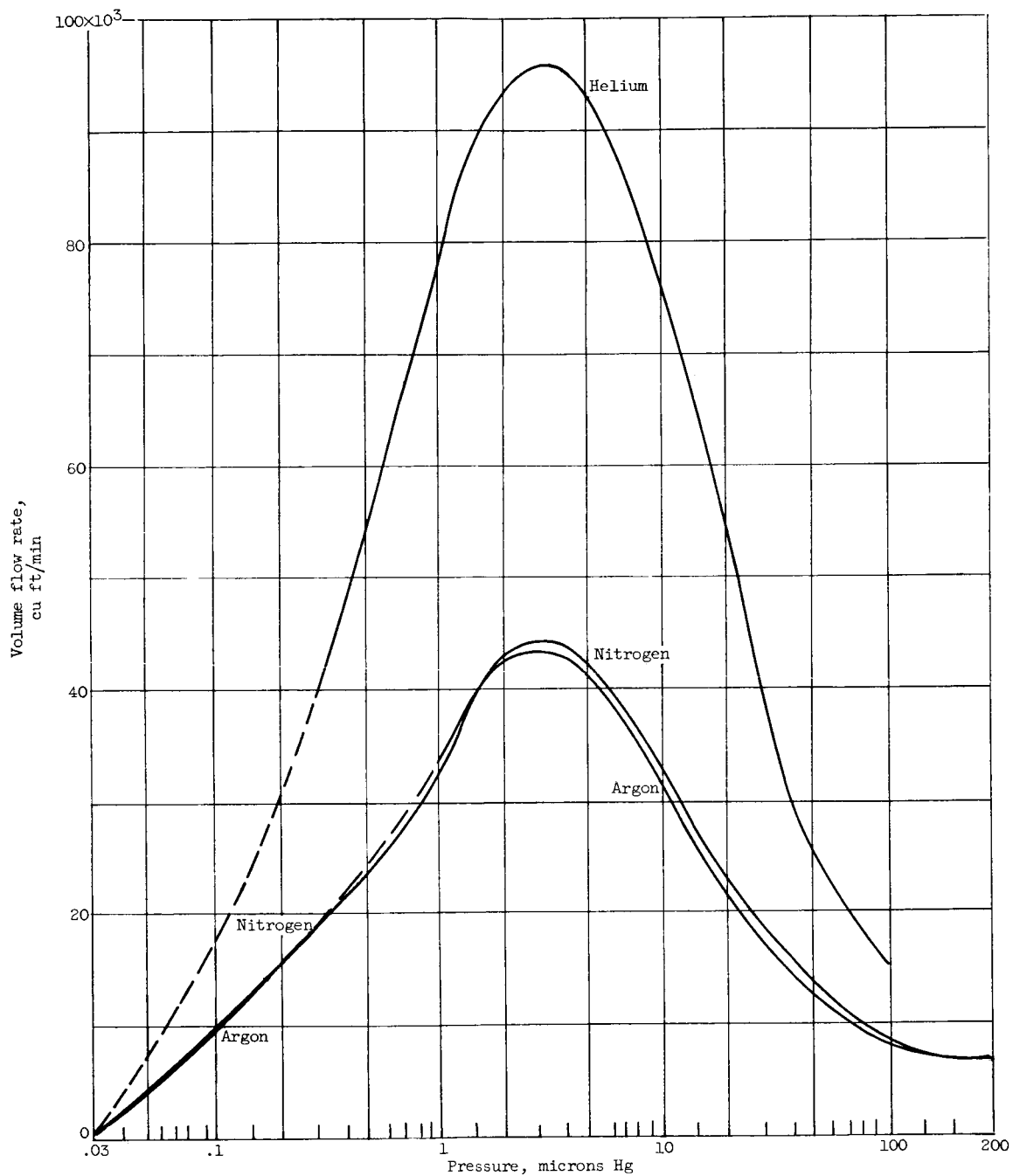
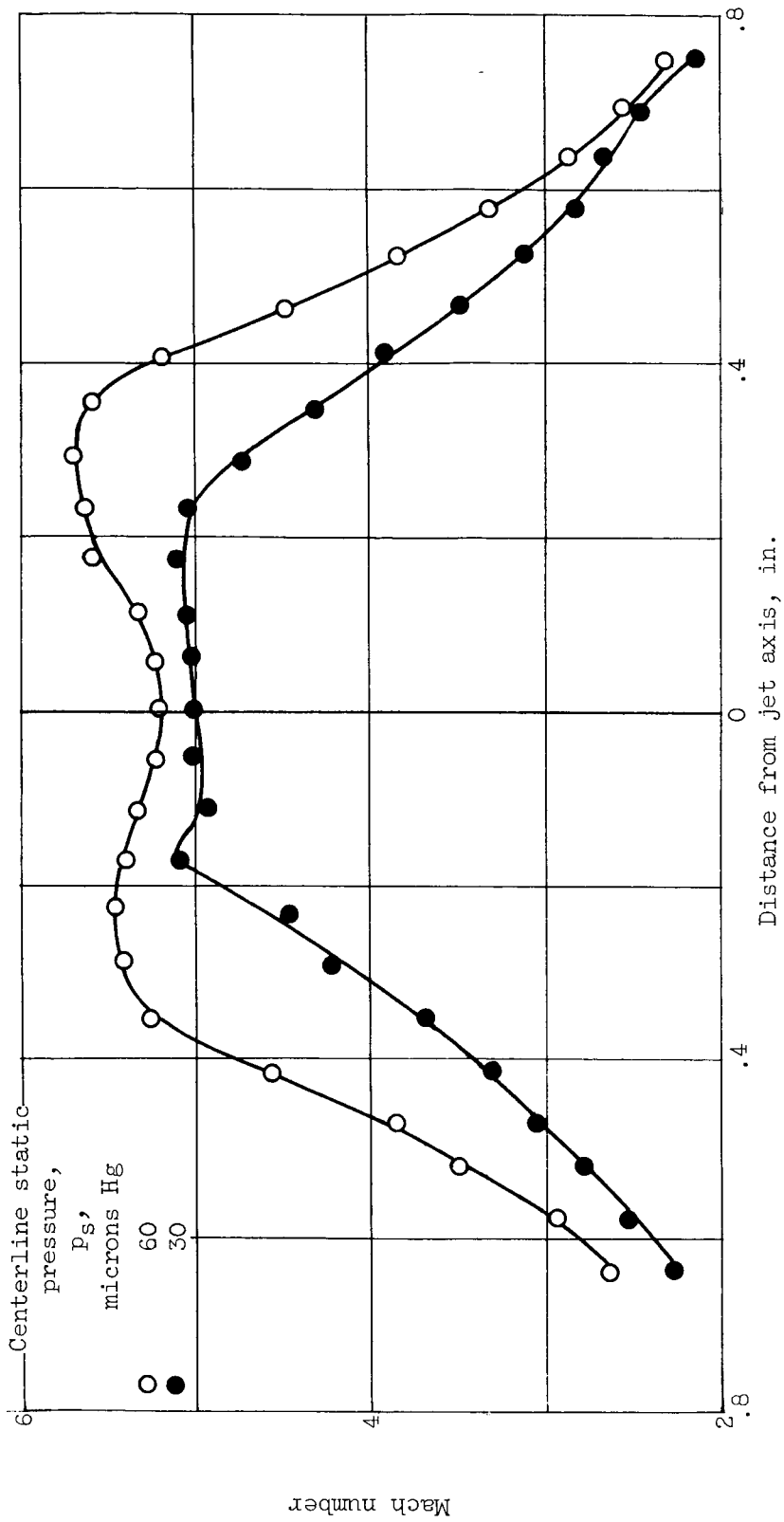


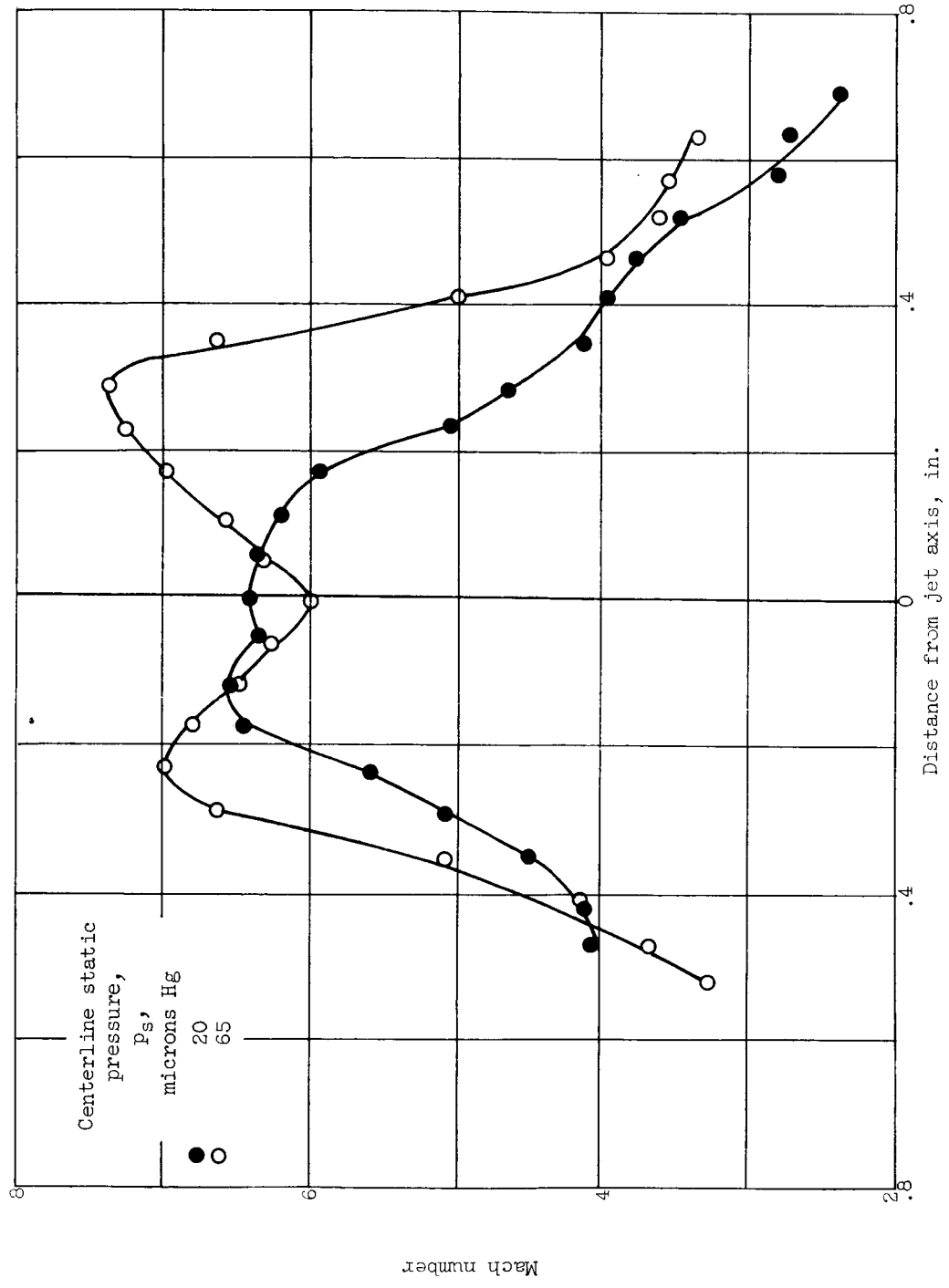
Figure 2. - Volume flow rate of low-density test facility.





(a) Nitrogen; nozzle 1.

Figure 3. - Mach number profiles along jet diameter 1.2 inches downstream from nozzle exit.



(b) Argon; nozzle 1.

Figure 3. - Continued. Mach number profiles along jet diameter 1.2 inches downstream from nozzle exit.

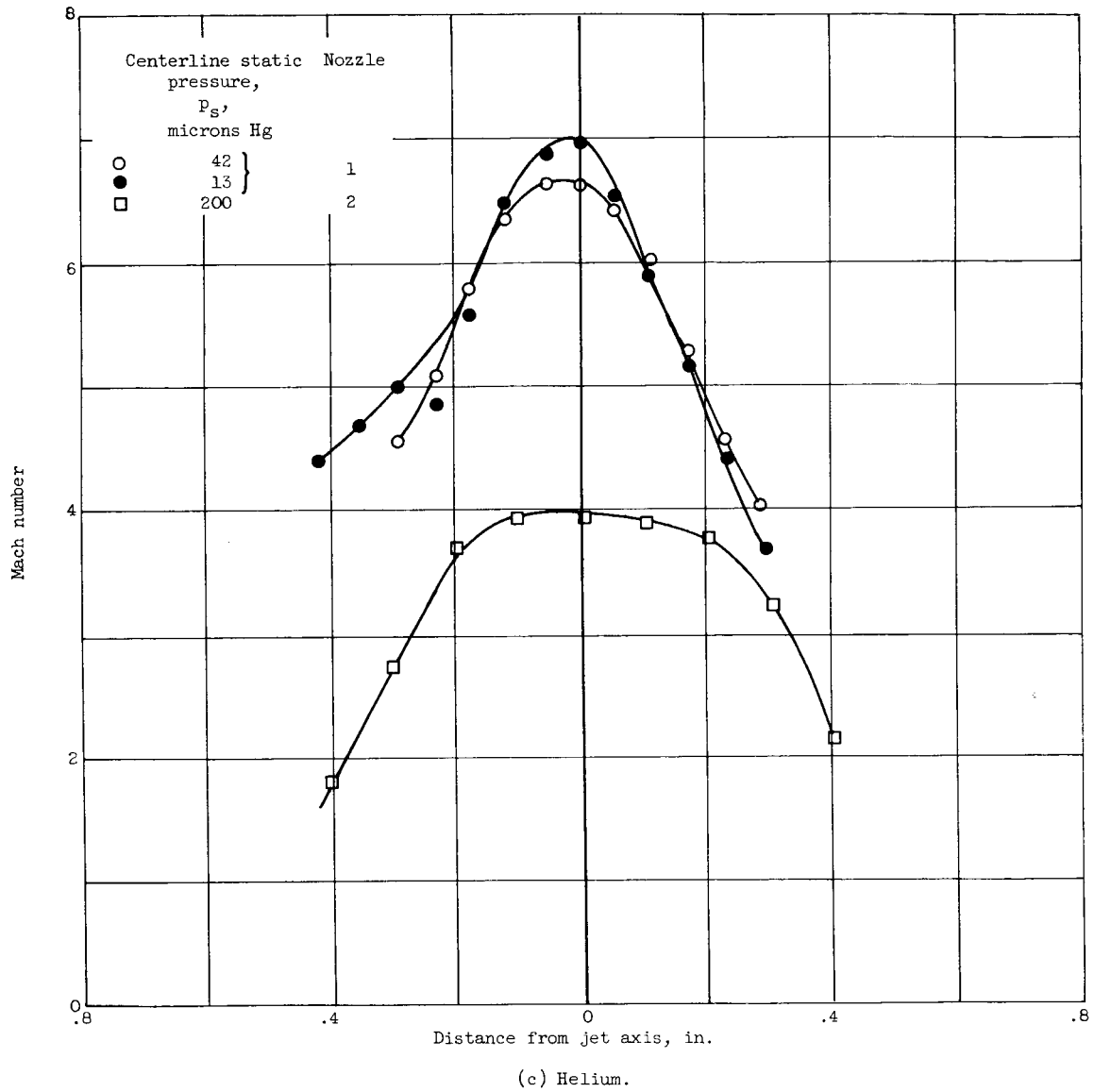
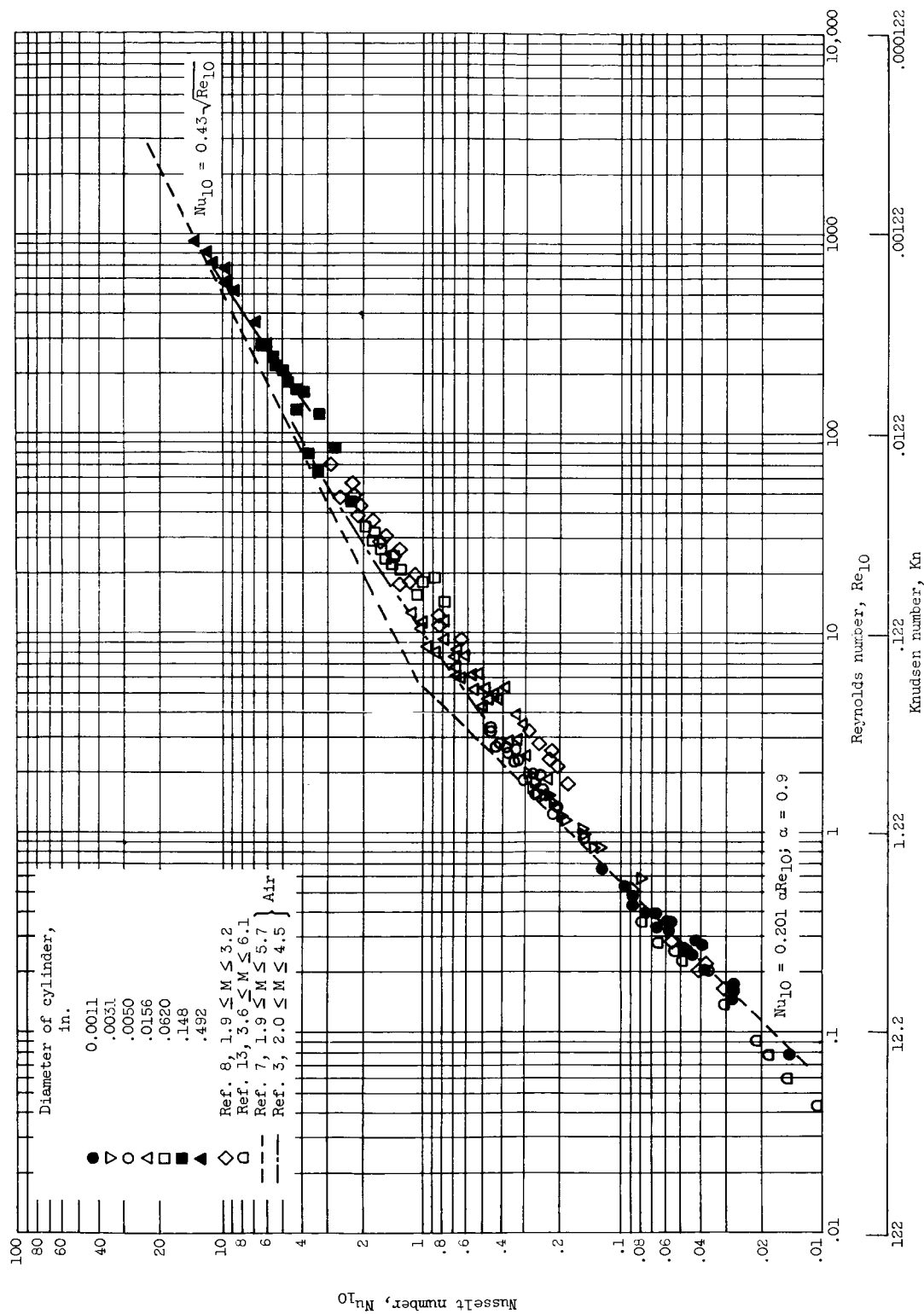
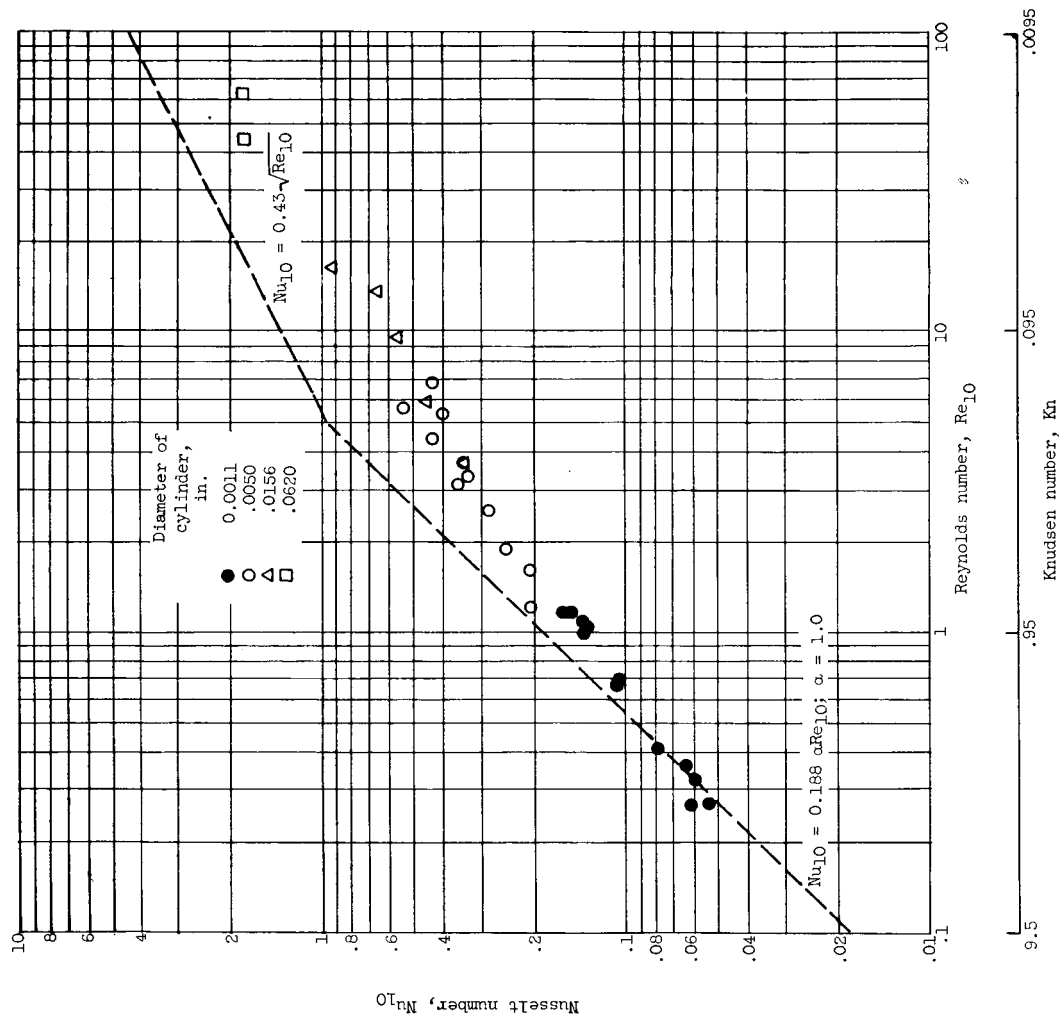


Figure 3. - Concluded. Mach number profiles along jet diameter 1.2 inches downstream from nozzle exit.



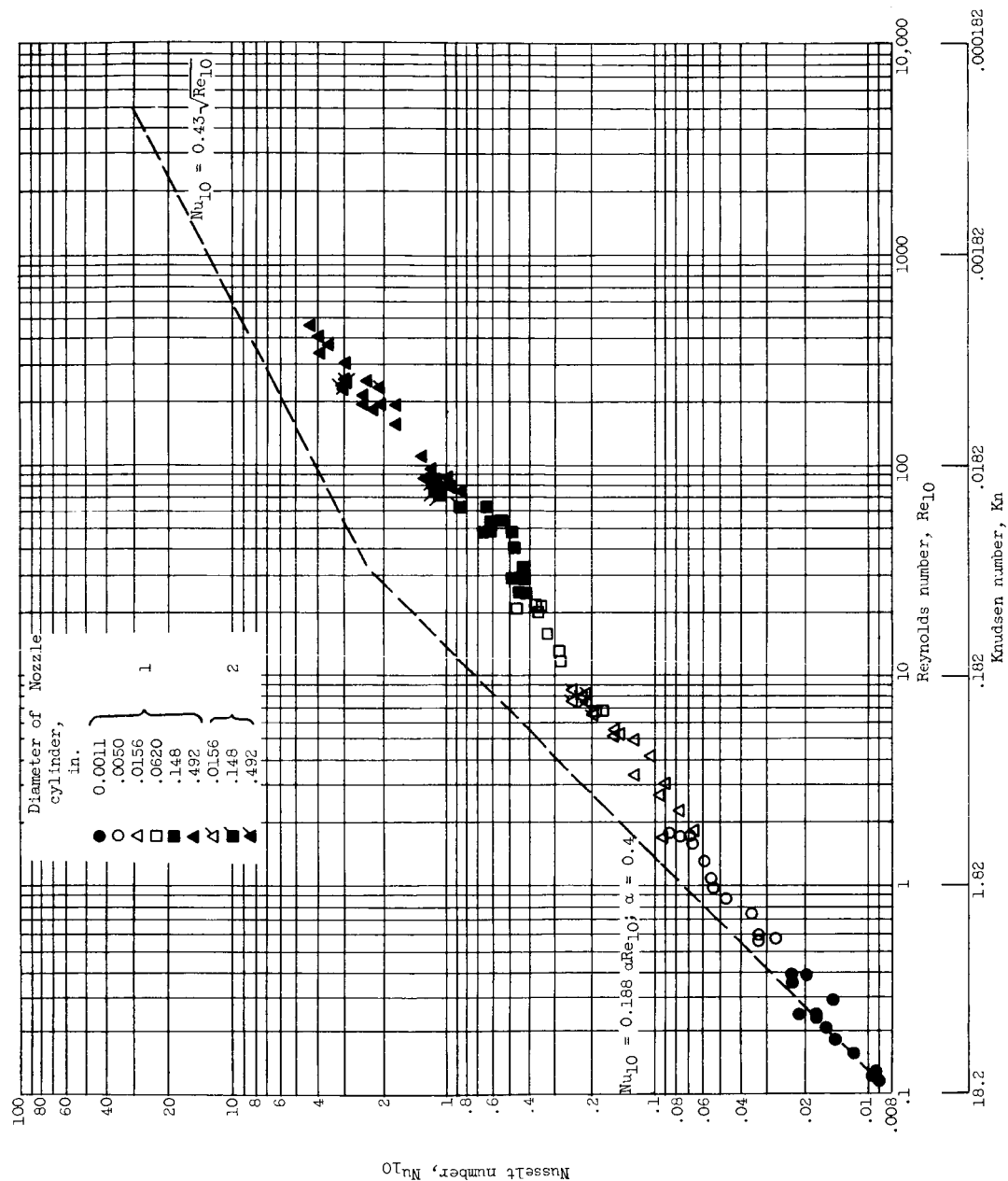
(a) Nitrogen; Mach number,  $M = 5$ ; nozzle 1; Knudsen number calculated for  $M = 5$ .

Figure 4. - Nusselt number as function of Reynolds number. Total temperature, 540° R.



(b) Argon; Mach number,  $M = 6$ ; nozzle 1; Knudsen number calculated for  $M = 6$ .

Figure 4. - Continued. Nusselt number as function of Reynolds number. Total temperature, 540° R.



(c) Helium; Mach number,  $M = 4$  and 7; Knudsen number calculated for  $M = 7$ .

Figure 4. - Concluded. Nusselt number as function of Reynolds number. Total temperature,  $540^{\circ} R$ .

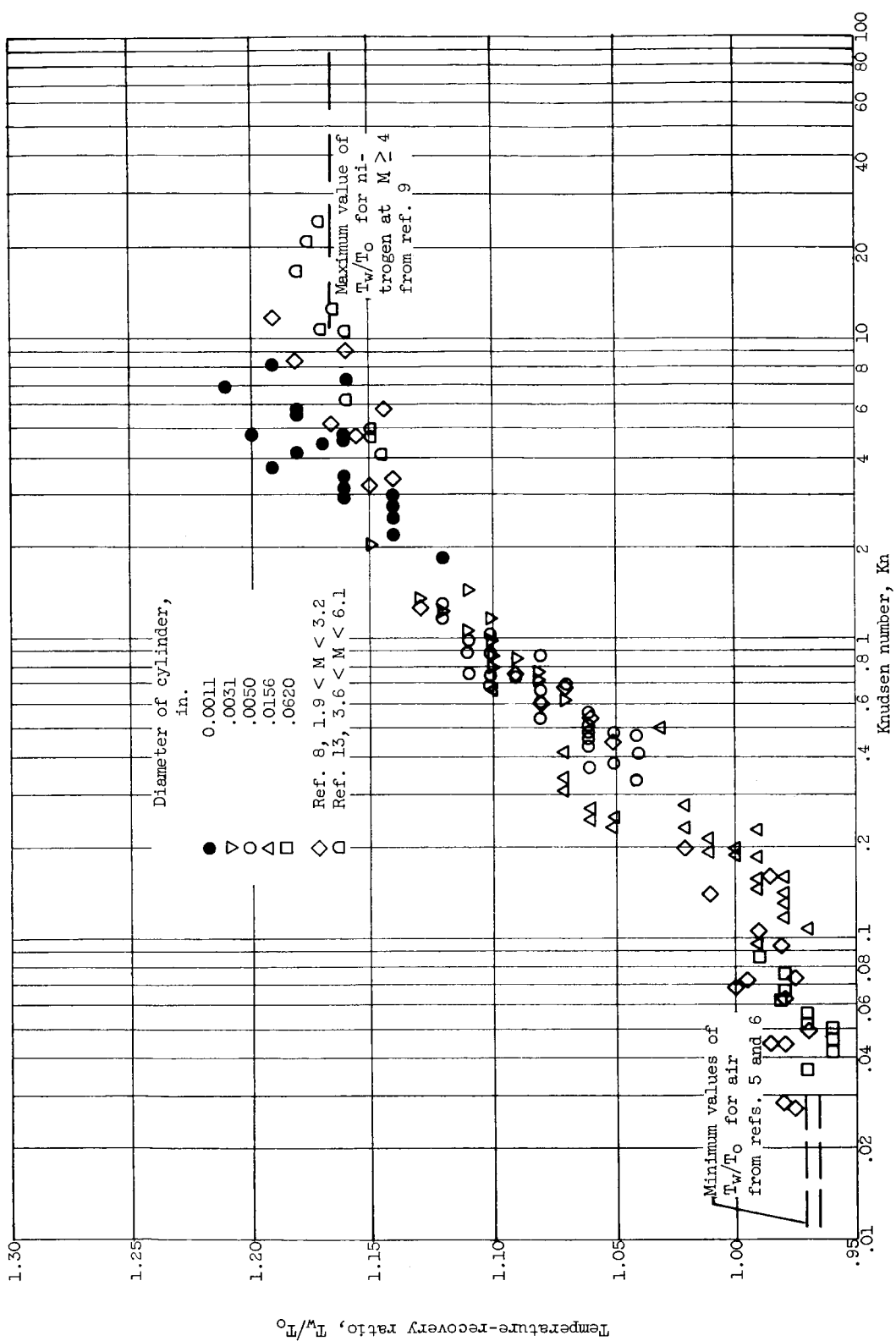
(a) Nitrogen; Mach number,  $M = 5$ .

Figure 5. - Temperature-recovery ratio as function of Knudsen number. Nozzle 1.

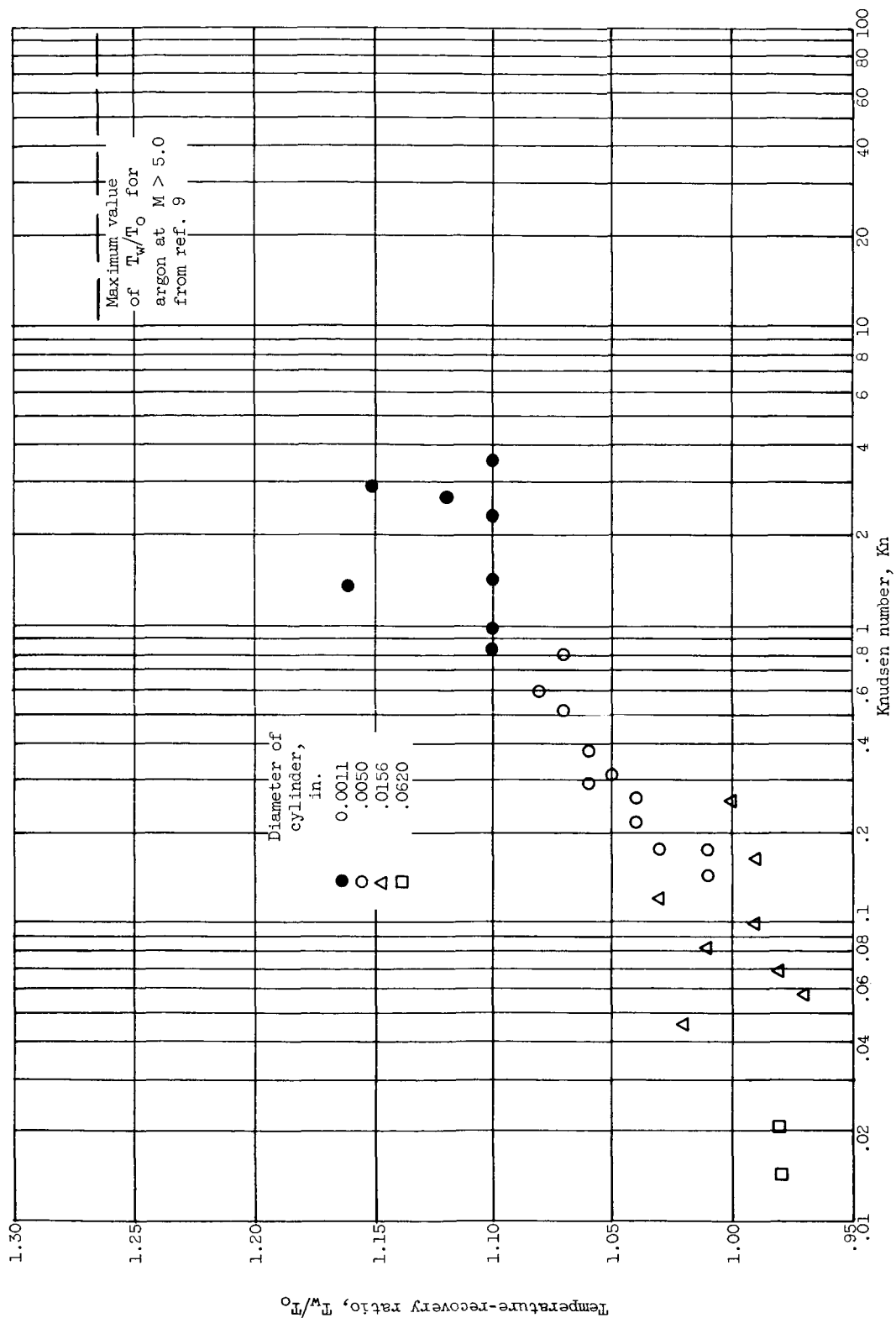
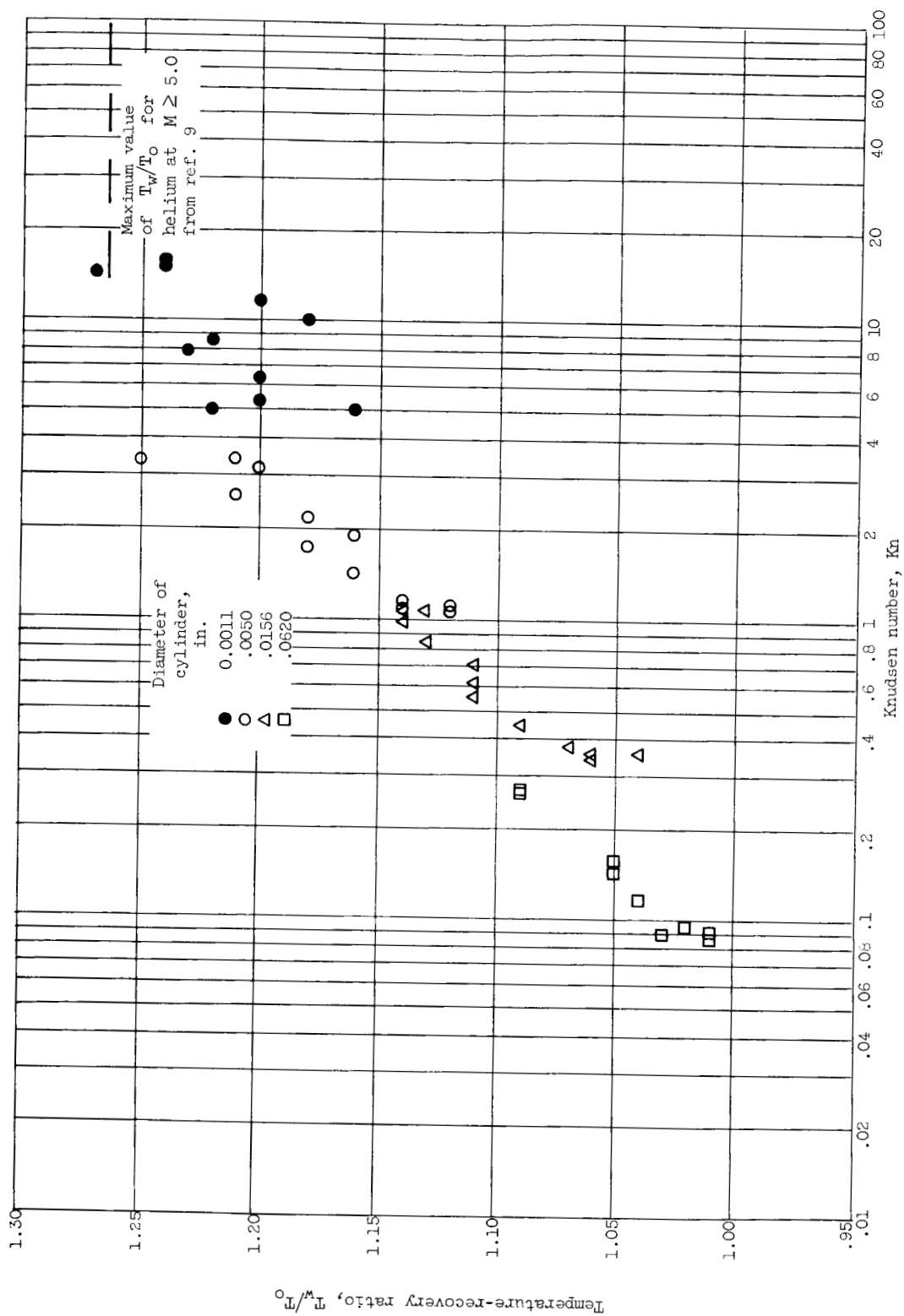
(b) Argon; Mach number,  $M = 6$ .

Figure 5. - Continued. Temperature-recovery ratio as function of Knudsen number. Nozzle 1.





(c) Helium; Mach number,  $M = 7$ .

Figure 5. - Concluded. Temperature-recovery ratio as function of Knudsen number. Nozzle 1.